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Memorandum

TO : J. Arlauskas, Technical Officer, Multi-Spectral Scanner, ERTS

DATE: April 6, 1972

FROM : M. P. Thekaekara
Test and Evaluation Division

SUBJECT: Solar Irradiance Measurements for the Calibration of the Multi-Spectral Scanner

Measurements were made to determine the total and spectral irradiance due to the Sun in order to ensure that the Multi-Spectral Scanner channels were set below the saturation limit and to permit a precise calibration of the MSS. The results are presented in a series of tables and figures.

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SOLAR IRRADIANCE MEASUREMENTS FOR THE CALIBRATION OF THE MULTI-SPECTRAL SCANNER

by M. P. Thekaekara

This report presents the results of a series of measurements made to determine the spectral irradiance of the Sun at two test sites in Santa Barbara, Cal., and on Table Mountain, Cal. These measurements were undertaken at the request of the Project Office of the Multi-Spectral Scanner experiment of the Earth Resources Technology Satellite. The purpose of these studies is to perform a pre-launch calibration of the MSS and in particular to ensure that the adjustments and settings in the different channels of the MSS, while ensuring optimum sensitivity and signals well above the noise level, do not, however, cause saturation and hence unreliability in the signals when the MSS is directed towards the Sun. The MSS is directed towards the Sun for a brief interval of time once during each orbit. The pulse heights during the solar scan are the primary source of calibration for the MSS. The four broadband wavelength isolation filters of the MSS span the range 0.5 to 1.1 μm. The solar irradiance and its spectral distribution in this range will be based on the Convair 990 data obtained by the Goddard experimenters (References 1, 2 and 3). Earlier calibrations of the MSS had been made using a large integrating sphere as the field of view. Such calibration while fully adequate for the scans of the terrestrial surface to be made by the MSS can be highly misleading for the solar scan. The Sun has a high and non-uniform radiance over a disc which subtends an angle of about half a degree at the instrument. Hence it was judged necessary to make a calibration of the MSS using the Sun as source and at the same time to scan the solar spectrum with the instrumentation which had been used in the Convair 990 project.

The plan as originally proposed was to make the measurements at Santa Barbara Research Center using the MSS and the Leiss quartz double prism monochromator. Since preliminary studies with the Leiss at GSFC showed certain problems arising out of its not having been used for a long time, it was later found necessary to use also the Perkin-Elmer LiF prism monochromator.

Measurements were first made with the Leiss at the SBRC on a patio between two buildings. This location proved to be unsatisfactory since most of the time the sky was cloudy. The sunshine was hazy and showed a high aureole effect. The MSS was used one afternoon, February 24, to scan different specimens of global terrain. At the same time the Leiss was directed towards the Sun. The MSS was not directed towards the Sun on February 24. Weather forecasts did not give hopes of satisfactory observing conditions for the subsequent days. Hence the test site was changed to Table Mountain, Cal., altitude 7200 ft. Measurements were made on February 26 and 27 using the MSS to track the Sun in many different channels (combinations of mirror facet, filter and detector) and the Perkin-Elmer and Leiss to determine the solar spectral irradiance. An Ångström pyrheliometer mounted on a heliostat was also used to measure the total irradiance of the Sun.

The three instruments, P. E., Leiss and Ångström have been described in literature (Ref. 3). The output of the Ångström when multiplied by its known calibration factor gives the total irradiance due to the Sun (including also a small portion of circumsolar sky of half-cone angle about 3°). The results are expressed on the International Pyrheliometric scale IPS 56. The standard of calibration for the Leiss and PE is the NBS type quartz iodine lamp. Three calibrated lamps were available. The output of these instruments was available as pen recorded Leeds and Northrup strip charts. Tape records suitable for computerized data analysis were not made. The solar spectrum was scanned almost continuously during the time the MSS was directed towards the Sun to scan the solar disc. Most of the solar spectral scans were in the wavelength range 0.4 to 1.2 μm. One scan with each instrument was made over the whole range, 0.3 to 2.6 μm. Studies were made also to determine the correction factors for sky radiation. All data were reduced by hand.

The results are presented in a series of charts and tables. They are sufficiently detailed to permit an accurate evaluation of the calibration constant for each combination of filter, detector and mirror facet. Since all these three are wavelength dependent and the spectrum of the Sun on Table Mountain is different from that outside the atmosphere, the spectral data at close wavelength intervals and especially in the H_2O absorption bands are essential for transfer of calibration from ground to space. The problem of calibration is discussed in a memorandum generated at SBRC (Cline, Upton and Yuh, memo to Wengler, 8 June, 1970). In the present calibration the integrating sphere and the quartz iodine lamp proposed in the memo are being replaced by the Sun itself. February 26 and 27 were days of bright sunshine on Table Mountain. The irradiance in the range 0.5 to 1.1 μm was 614 $W \cdot m^{-2}$ compared to 701 $W \cdot m^{-2}$ in the same range outside the atmosphere. There are several H_2O absorption bands in this range, but being dry wintry days, the amount of precipitable water in the path of the Sun was about 2mm, very low compared to 19mm which is the average at sea level for mid latitudes.

Table I gives the total irradiance of the Sun on 24, 26 and 27 February during the periods when the MSS was in operation. These values were obtained by Charles H. Duncan of GSFC using an Ångström pyrheliometer. The values are in units of $mW \cdot cm^{-2}$. Figure 1 gives the same results in graphical form. The units are given also in $W \cdot m^{-2}$ in agreement with the rest of the tables and graphs.

Table II presents the spectral irradiance data on Table Mountain for February 26 and 27. It is based on the spectral scans made by the P.E. and Leiss, taking into account also the total irradiance as given by the Ångström and the effect of the narrow H_2O bands between 0.5 and 0.9 μm. The irradiance is that of the whole of the solar disc, excluding the circum-solar sky. The first column gives the wavelengths in μm. They are 0.01 μm apart except at the absorption bands where closer intervals adequate for showing the width and depth of the bands have been chosen. The second column E_o gives solar spectral irradiance outside the atmosphere (zero air mass) at 1 A.U. (average Sun-Earth distance). The actual Sun-Earth distance for the three days of measurement was very close to the average: 24th : 0.989 505 A.U.; 26th : 0.989 955 A.U.; and 27th : 0.990 186 A.U. The values of E_o are from Reference 1. The next three columns give the spectral irradiance per unit area exposed normally to the Sun's rays for three values of air mass (secant of solar zenith angle). The three final columns give the atmospheric absorbance at Table Mountain for the three air mass values. It is the ratio of the irradiance at a given air mass to that for air mass 0.

Figures 2 through 5 present graphically the data of 2, 3, 4 and 5 of Table II.

Table III gives the integrated values of solar irradiance in wide spectral bands of interest to the MSS.

Table IV gives the air mass solar zenith angle as a function of time on Table Mountain and at SBRC. It should be noted that the air mass as defined here refers to the altitude of the location and not to sea level, so that air mass is equal to the secant of the solar zenith angle. It is computed from known values of latitude, longitude, ephemeris transit and solar declination. Corrections for air mass due to atmospheric refraction were not significant for these low values of zenith angle.

Figure 6 presents graphically the zenith angle and air mass values for Table Mountain.

Table 5 gives a complete listing of solar spectral irradiance for air mass zero and one A.U.

Figure 7 presents the data graphically for the range 0.1 to 2.6 μm. The figure also gives the solar irradiance at sea level for Sun and sky for unit air mass and for a very clear atmosphere. The area under this spectral curve is 1111 $W \cdot m^{-2}$ which represents nearly the maximum observed for mid latitudes. This curve is based on measurements made at two locations by G. Daniels over a ten year period (Reference 4).

Solar spectral irradiance on Table Mountain over the whole wavelength range 0.3 to 3 μm is given in Table VI. These results are listed for air mass 1.5. The measurements were made on February 27. The integrated irradiance from 0 to λ is also given. The irradiance below 0.3 μm is insignificant because of ozone absorption. The total irradiance due to the solar disc is 1027 $W \cdot m^{-2}$, which is slightly lower than the value measured by the Ångström which views also a small portion of the circumsolar sky. The spectral curve is shown graphically in Figure 8.

Solar and sky spectral irradiance data for the afternoon of February 24 at the SBRC experimental site are given in Table VII and Figures 9 and 10.

The solar data are for air mass 1.5, time 1320 hrs., and give the energy received per unit area exposed normally to the Sun's rays (cos z = 0.6667; z = 48.2°). The MSS was directed toward different samples of vegetation and types of ground terrain. The irradiance on these surfaces was due to the Sun and the sky. Energy received per unit horizontal area due to the Sun is found by multiplying the values of $E_{\lambda sun}$ by 0.6667. E_λ for other values of solar zenith angle are found from the equation

$$E_{\lambda M} = E_{\lambda o}\, \alpha^M \text{ where } \alpha = \left[\frac{E_{\lambda\, 1\cdot 5}}{E_{\lambda o}}\right]^{2/3}$$

$E_{\lambda M}$ is the irradiance for air mass M; $E_{\lambda o}$ for air mass zero; α is the attenuation due to the atmosphere for Sun at zenith.

The sky irradiance data are given in Table VII under the column $E_{\lambda sky}$. This includes the components due to Rayleigh, ozone and aerosol scattering from the whole sky.

Note that the scale for the y-axis in Figure 10 is four times that in Figure 9.

Total irradiance per unit horizontal area at 1320 hrs. is (848 x 2/3 + 116 =) 681 $W \cdot m^{-2}$. Sky irradiance remained practically the same during the test period.

The author wishes to acknowledge the cooperation of C. H. Duncan who coordinated the project and made the total irradiance measurements, A. R. Winker for the operation of the Perkin-Elmer and data reduction, S. G. Park for the operation of the Leiss, T. A. Riley, J. A. Henegar and G. F. Stitt for data reduction.

References:

1. Anon: Solar Electromagnetic Radiation, NASA SP 8005, (NASA Washington, D. C.) May 1971.

2. Thekaekara, M. P.; and Drummond, A. J.: Standard Values for the Solar Constant and its Spectral Components. Nature, Physical Sciences, vol. 229, no. 1, Jan. 4, 1971, pp. 6-9.

3. Thekaekara, M. P., ed.: The Solar Constant and the Solar Spectrum Measured from a Research Aircraft, NASA TR R-351 (Washington, D. C.) Oct. 1970.

4. Anon: Surface Atmospheric Extremes, NASA SP 8084, (NASA, Washington, D. C.) February 1972.

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TABLE 1

TOTAL IRRADIANCE MEASUREMENTS FOR ERTS MSS

Date: 24 February 1972
Place: Santa Barbara Research Center, CA
Weather: High clouds, hazy sunshine, much aureole

Time	Total Irradiance
1240	86.2 mw cm^{-2}
1250	88.5
1300	89.5
1310	89.9
1320	89.0
1325	89.1
1330	89.4
1340	88.3
1345	88.9
1350	88.5
1355	89.0
1400	88.6
1405	88.5
1410	87.8
1415	87.5
1425	87.1

Date: 26 February 1972
Place: Table Mountain, CA
Weather: Windy, thin high clouds

Time	Total Irradiance	
1135	105.0 mw cm^{-2}	
1140	105.4	
1145	106.1	
1150	106.2	
1155	106.1	
1200	105.9	
1205	106.5	
1210	106.3	
1215	106.4	
1220	107.0	
1225	105.8	low
1230	105.4	clouds ↓
1235	101.4	
1310	103.4	
1320	105.4	
1325	105.7	
1330	104.6	
1335	104.8	
1340	104.2	
1345	104.7	
1350	104.0	
1355	104.5	
1400	103.2	
1405	103.6	

Date: 27 February 1972
Place: Table Mountain, CA
Weather: slight wind, thin cirrus clouds

Time	Total Irradiance
1015	105.4 mw cm^{-2}
1020	105.5
1025	105.5
1030	105.5
1035	105.5
1040	105.5
1045	105.5
1050	105.6
1055	105.7
1100	105.6
1105	105.0
1110	105.4
1115	105.3
1120	105.4
1125	105.5
1130	105.5
1135	105.8
1140	106.1
1145	106.1
1150	106.0
1155	105.8
1200	106.3
1215	105.6
1220	106.8
1225	105.9
1230	105.6
1235	105.5
1240	105.6
1245	105.0
1250	105.6
1255	105.4
1300	104.3
1315	104.3

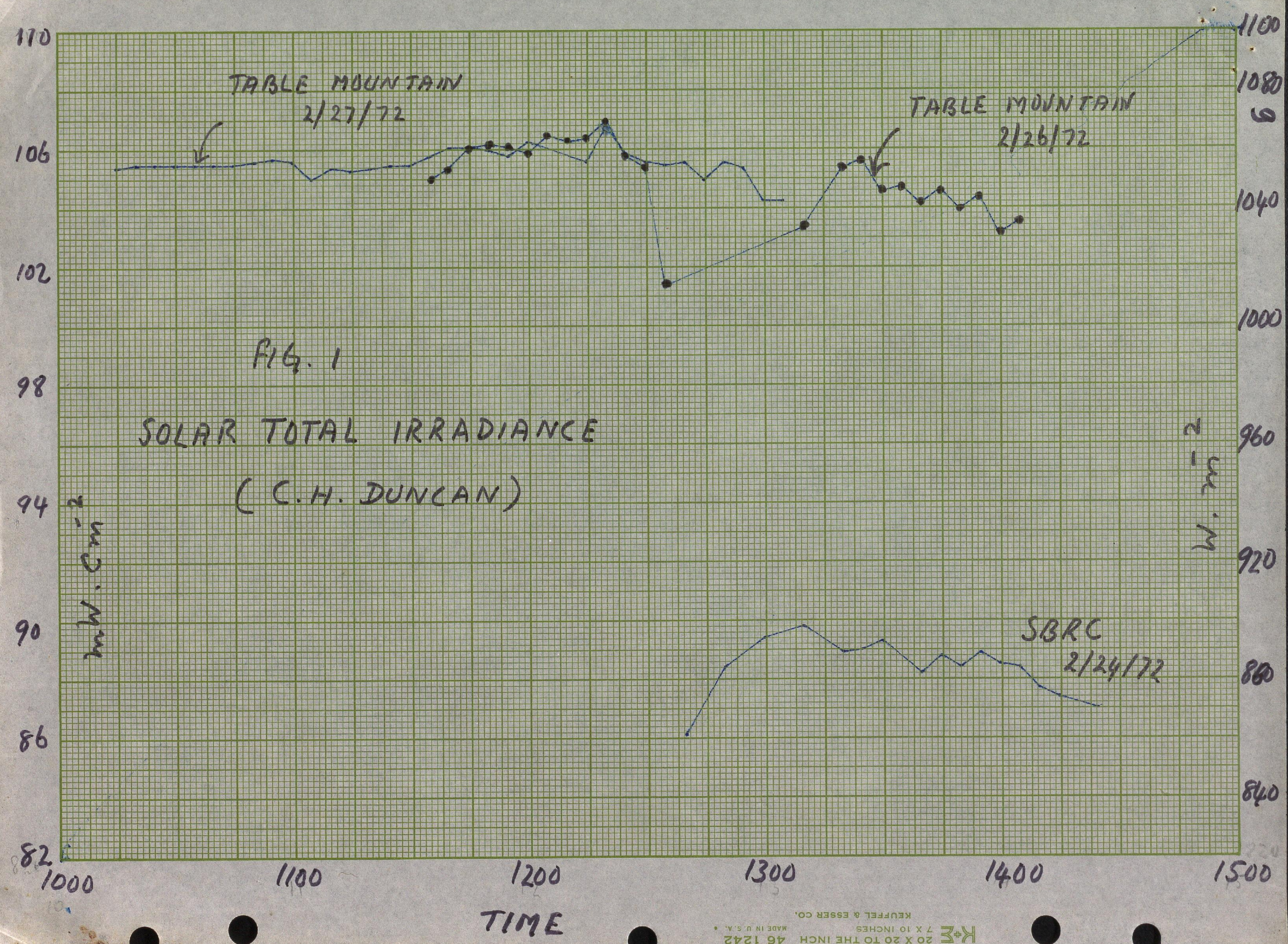


TABLE MOUNTAIN
2/27/72
TABLE MOUNTAIN
2/26/72
FIG. 1
SOLAR TOTAL IRRADIANCE
(C.H. DUNCAN)
SBRC
2/24/72
mW.cm⁻²
W.m⁻²
110
106
102
98
94
90
86
82
1100
1080
1040
1000
960
920
880
840
1000
1100
1200
1300
1400
1500
TIME

10 1

TABLE II

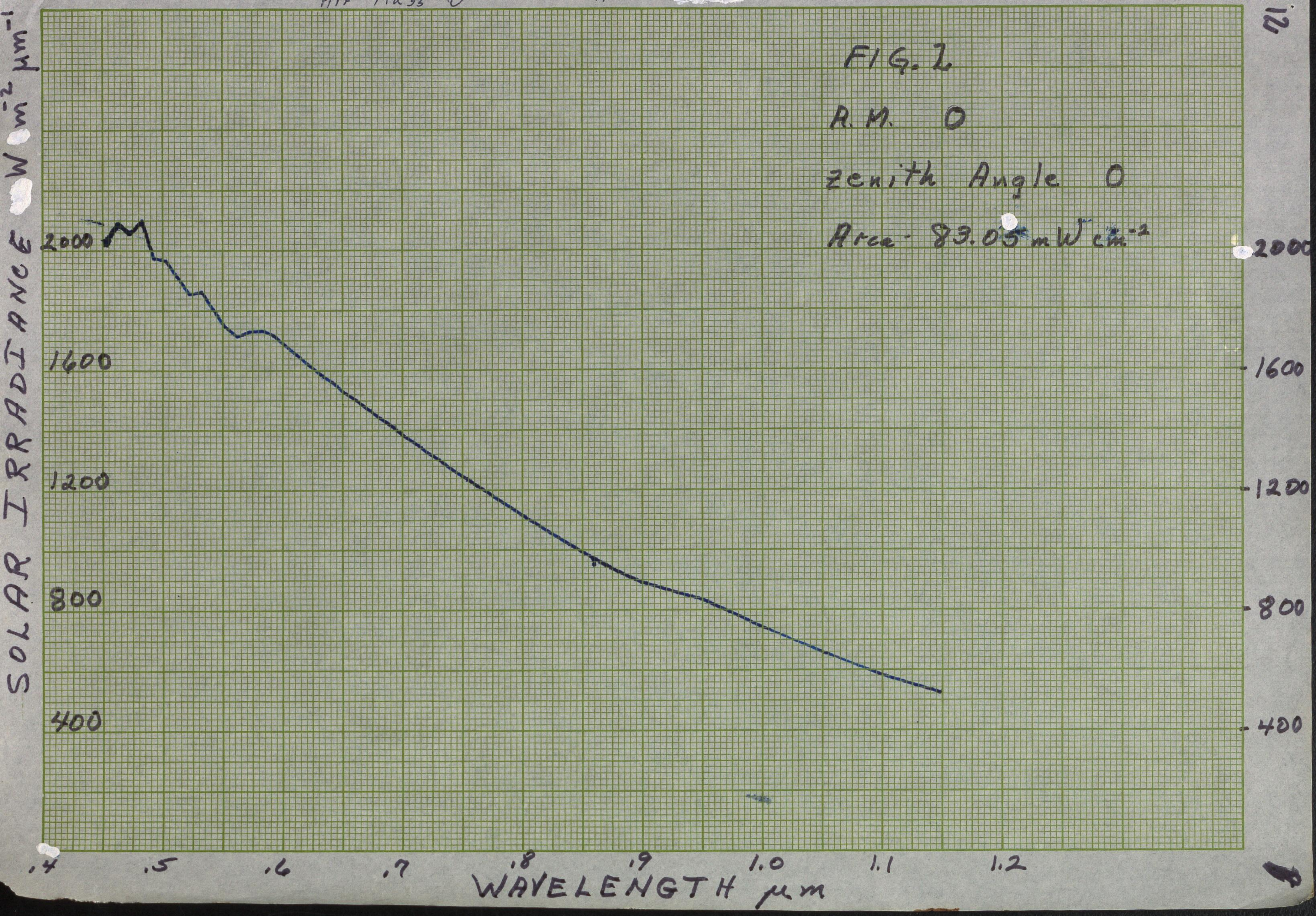
SOLAR SPECTRAL IRRADIANCE, E, for ZERO AIR MASS AND FOR SECANT OF ZENITH ANGLE 1.4, 1.5 & 1.6; ATMOSPHERIC ATTENUATION a ~~fo~~ FOR SEC Z 1.4, 1.5, 1.6   P in $W m^{-2} \mu m^{-2}$

λ	E_0	$E_{1.4}$	$E_{1.5}$	$E_{1.6}$	$a_{1.4}$	$a_{1.5}$	$a_{1.6}$
.45	2006	1421	1386	1352	.708	.691	.674
.46	2066	1506	1473	1440	.729	.713	.697
.47	2033	1550	1520	1491	.762	.748	.733
.48	2074	1596	1566	1537	.769	.755	.741
.49	1950	1569	1545	1521	.805	.792	.780
.50	1942	1555	1530	1506	.800	.788	.775
.51	1888	1513	1490	1467	.804	.792	.779
.52	1833	1487	1465	1443	.811	.799	.787
.53	1842	1473	1450	1427	.800	.787	.775
.54	1783	1460	1439	1419	.819	.807	.796
.55	1725	1422	1403	1384	.825	.813	.802
.56	1695	1395	1376	1357	.823	.812	.801
.57	1712	1405	1385	1364	.821	.809	.798
.58	1715	1420	1401	1382	.828	.817	.806
.59	1700	1404	1385	1366	.826	.815	.804
.60	1666	1391	1373	1355	.835	.824	.814
.61	1635	1376	1359	1342	.842	.831	.821
.62	1602	1365	1350	1335	.852	.843	.833
.63	1570	1354	1340	1326	.863	.854	.845
.64	1544	1349	1336	1323	.874	.865	.857
.65	1511	1332	1320	1308	.882	.874	.866
.66	1486	1323	1312	1301	.890	.883	.876
.67	1456	1300	1290	1280	.893	.886	.879
.68	1427	1288	1279	1270	.903	.896	.890
.685	1415	1257	1246	1235	.888	.881	.873
.687	1410	1227	1215	1203	.870	.862	.853
.688	1407	1250	1240	1229	.889	.881	.874
.69	1402	1264	1255	1246	.902	.895	.889
.70	1369	1250	1242	1234	.913	.907	.901
.71	1344	1233	1225	1217	.917	.911	.906
.72	1314	1212	1205	1198	.922	.917	.912
.724	1304	1169	1160	1151	.897	.890	.883
.725	1302	1150	1140	1130	.883	.876	.868
.73	1290	1187	1180	1173	.920	.915	.909
.74	1260	1168	1162	1156	.927	.922	.917
.75	1235	1127	1120	1113	.913	.907	.901
.753	1228	1052	1040	1029	.856	.847	.838
.757	1218	1126	1120	1114	.925	.920	.914
.76	1211	1126	1120	1114	.930	.925	.920
.77	1185	1101	1095	1089	.929	.924	.919
.78	1159	1085	1080	1075	.936	.932	.927
.79	1134	1060	1055	1050	.935	.930	.926
.80	1109	1042	1037	1032	.939	.935	.931
.802	1104	993	985	978	.899	.892	.885
.805	1097	1025	1020	1015	.934	.930	.925
.81	1085	1015	1010	1005	.935	.931	.926
.82	1060	999	995	991	.943	.939	.935
.83	1036	974	970	966	.940	.936	.932
.836	1022	964	960	956	.943	.939	.935
.84	1013	888	880	872	.877	.869	.861
.844	1004	935	930	925	.931	.926	.922
.85	990	940	936	933	.949	.945	.942
.86	968	914	910	906	.944	.940	.936
.87	947	889	885	881	.939	.935	.930

TABLE II CONTD.

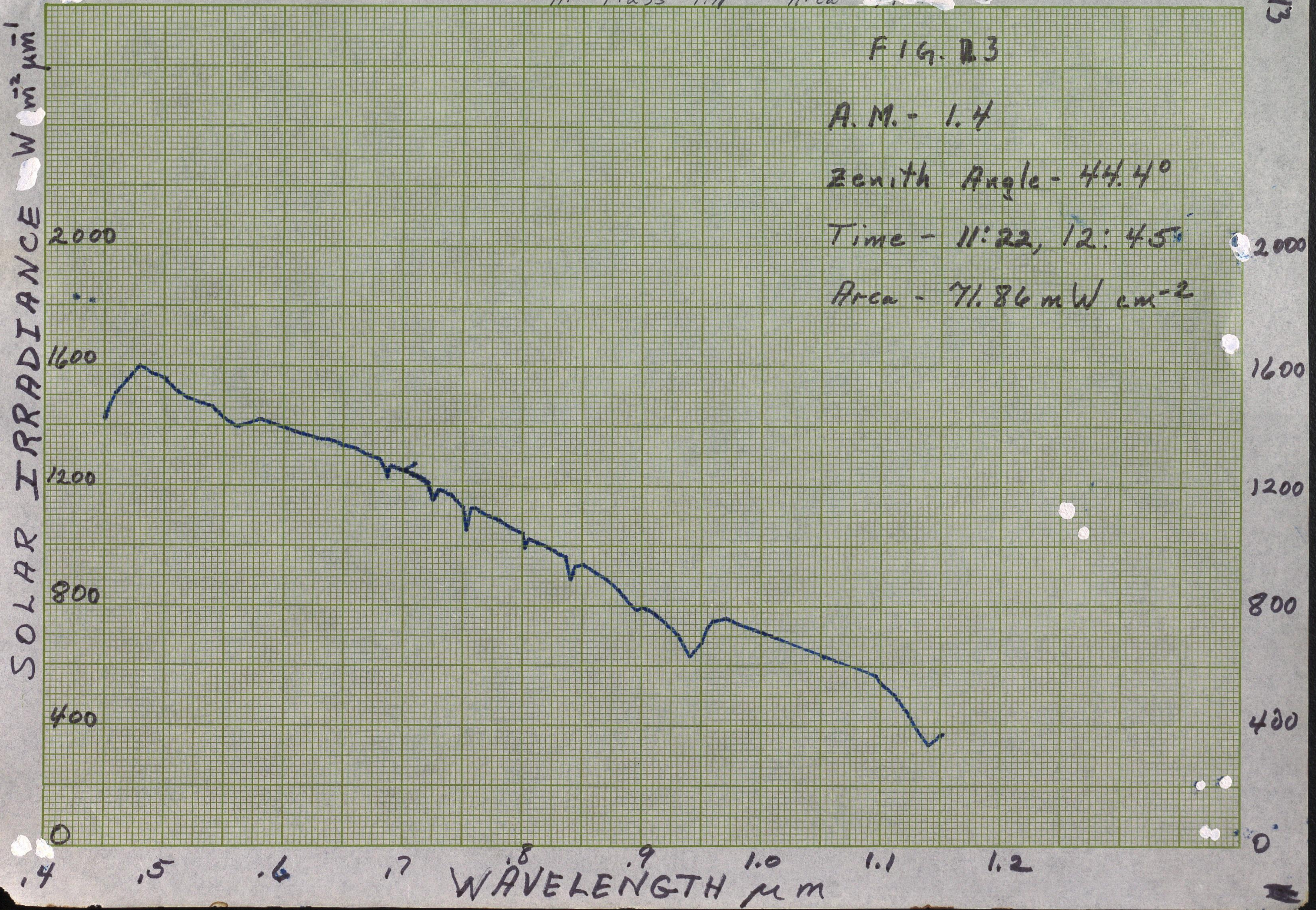
λ	E_0	$E_{1.4}$	$E_{1.5}$	$E_{1.6}$	$a_{1.4}$	$a_{1.5}$	$a_{1.6}$
.88	926	855	850	845	.923	.918	.913
.89	908	807	800	793	.889	.881	.874
.895	900	787	780	773	.875	.867	.858
.90	891	796	790	784	.894	.887	.880
.91	880	777	770	763	.863	.875	.867
.92	869	743	735	727	.855	.846	.836
.93	858	705	695	685	.821	.810	.799
.94	847	633	620	607	.747	.732	.717
.95	837	680	670	660	.812	.800	.789
.955	829	732	725	719	.884	.875	.869
.96	820	754	750	746	.920	.915	.909
.97	803	763	760	757	.950	.946	.943
.98	785	743	740	737	.946	.943	.939
.99	767	728	725	722	.849	.945	.942
1.0	748	715	713	711	.956	.953	.950
1.05	668	639	637	635	.957	.954	.951
1.095	601	572	570	568	.952	.948	.945
1.1	593	543	540	537	.916	.911	.905
1.11	581	510	505	500	.877	.869	.861
1.12	570	457	450	443	.802	.789	.777
1.13	558	390	380	370	.699	.681	.664
1.139	548	341	330	319	.623	.602	.582
1.15	535	379	370	361	.709	.692	.675

Air Mass 0 Area = 83.05



71.86

Air Mass 1.4 Area



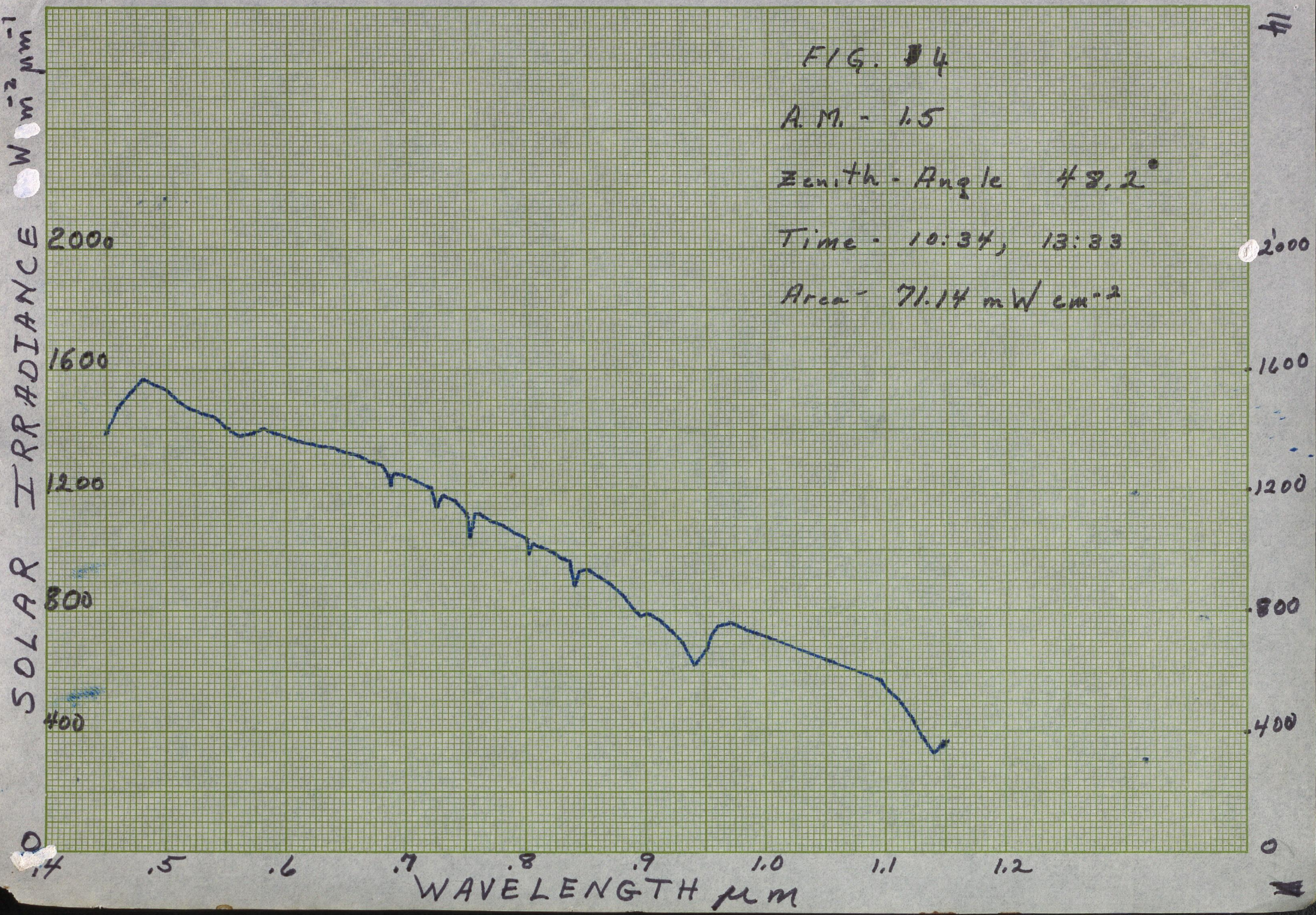


FIG. #4
A. M. - 1.5
Zenith - Angle 48.2°
Time - 10:34, 13:33
Area - 71.14 mW cm⁻²
SOLAR IRRADIANCE W m⁻² μm⁻¹
2000
1600
1200
800
400
0
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
WAVELENGTH μm

Air Mass = 1.6 Area = 70.43

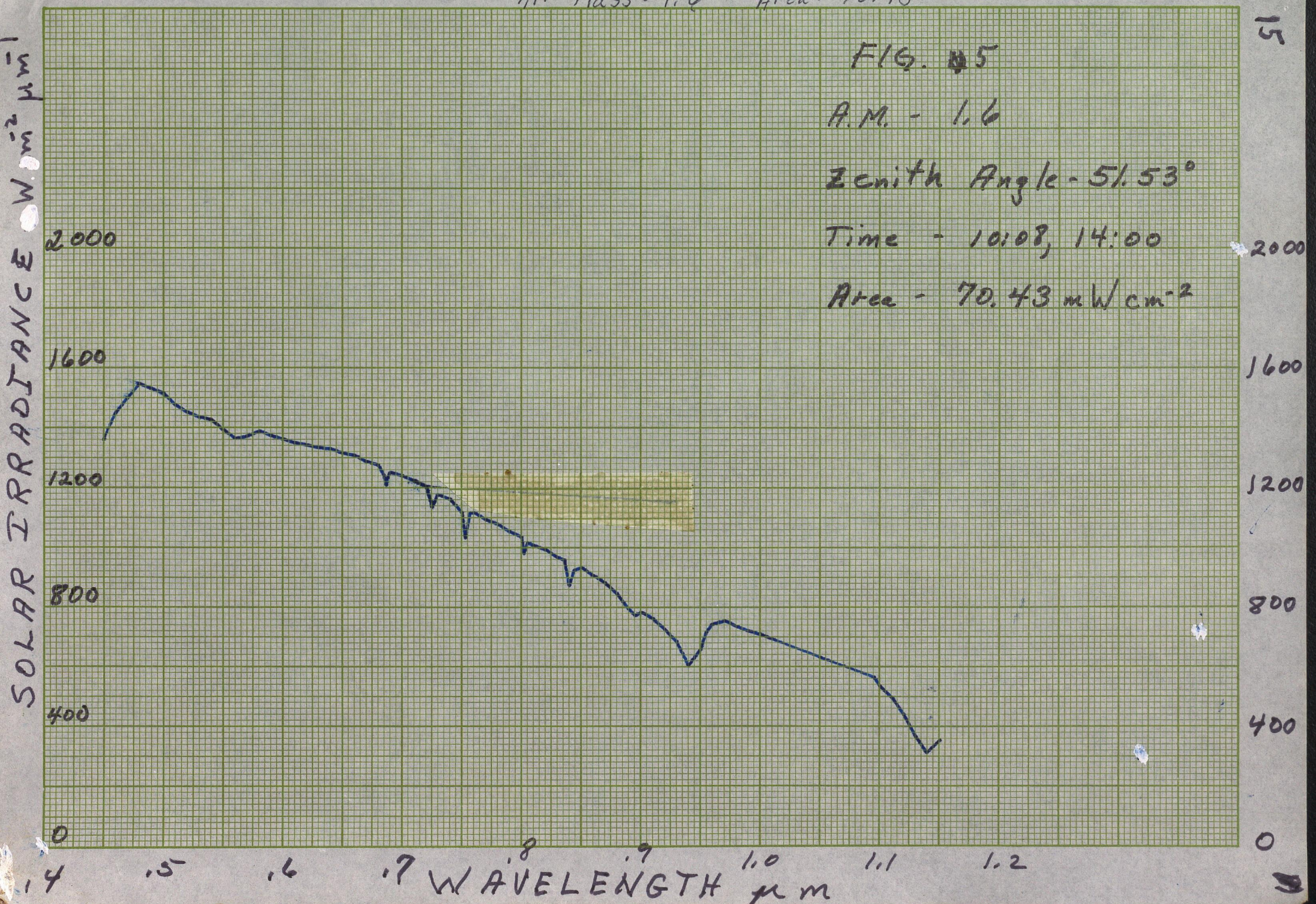


Table III

Integrated values of Solar Irradiance at Table Mountain, for wavelength range 0.45μ to λ (wavelength in μm; irradiance in $W \cdot m^{-2}$) on February 26 and 27 for air mass 0, 1.4, 1.5 and 1.6

λ \ AIR MASS	0.0	1.4	1.5	1.6
.45	0	0	0	0
.5	101.0	77.1	75.6	74.2
.6	277.9	221.6	218.1	214.6
.7	429.4	354.2	349.4	344.7
.8	553.2	468.1	462.7	457.3
.9	652.5	560.3	554.3	548.5
1.0	735.3	633.2	626.6	620.0
1.1	802.3	697.0	690.2	683.5
1.15	830.5	718.6	711.4	704.3

TABLE IV

Air Mass and Solar Zenith Angle for Table Mountain on February 26 + 27 and Santa Barbara Research Center on February 24, 1972

Time	Table Mountain		SBRC	
	Air Mass	Solar Zenith Angle (degrees)	Air Mass	Solar Zenith Angle (degrees)
0940	1.75	55.1	1.89	58.1
1000	1.63	52.3	1.75	55.3
1008	1.60	51.3		
1020	1.55	49.8	1.65	52.7
1034	1.50	48.2		
1040	1.48	47.6	1.57	50.5
1100	1.44	45.8	1.51	48.6
1120	1.40	44.4	1.47	47.1
1122	1.40	44.4		
1140	1.38	43.5	1.44	46.0
1200	1.37	43.3	1.43	45.5
1214	1.37	43.3		
1220	1.38	43.5	1.42	45.4
1240	1.39	44.2	1.44	45.8
1245	1.40	44.4		
1300	1.42	45.3	1.46	46.7
1320	1.46	46.9	1.50	48.1
1333	1.50	48.2		
1340	1.52	48.9	1.55	49.9
1400	1.60	51.3	1.62	52.0
1420	1.70	54.1	1.72	54.5
1440	1.83	57.0	1.85	57.2
1500	2.01	60.2	2.01	60.2

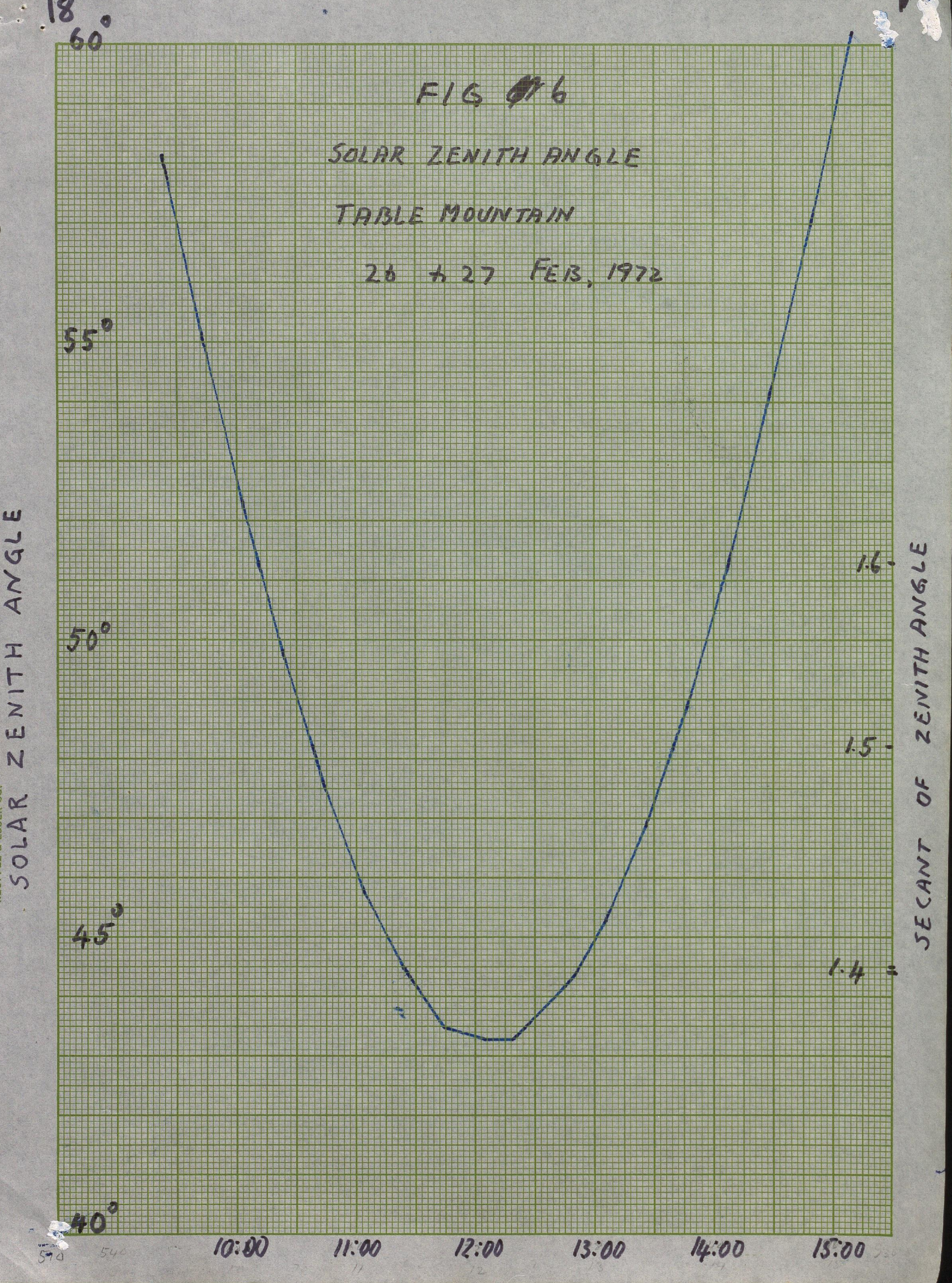


FIG #6
SOLAR ZENITH ANGLE
TABLE MOUNTAIN
26 & 27 FEB, 1972
60°
55°
50°
45°
40°
SOLAR ZENITH ANGLE
1.6
1.5
1.4
SECANT OF ZENITH ANGLE
10:00
11:00
12:00
13:00
14:00
15:00

19

TABLE 5

SOLAR SPECTRAL IRRADIANCE - PROPOSED STANDARD CURVE

λ - Wavelength in micrometers

E_λ - Solar spectral irradiance averaged over small bandwidth centered at λ, in $W \cdot m^{-2} \cdot \mu m^{-1}$

$E_{o-\lambda}$ - Integrated solar irradiance in the wavelength range o to λ, in $W \cdot m^{-2}$

$D_{o-\lambda}$ - Percentage of solar constant associated with wavelengths shorter than λ.

Solar constant - 1353 $W \cdot m^{-2}$

Note: lines indicate change in wavelength interval of integration.

λ	E_λ	$E_{o-\lambda}$	$D_{o-\lambda}$	λ	E_λ	$E_{o-\lambda}$	$D_{o-\lambda}$	λ	E_λ	$E_{o-\lambda}$	$D_{o-\lambda}$
.120	.100	.0059992	.00044	.525	1852	352.591	26.059	1.70	202	1221.23	90.261
.140	.030	.0072999	.00053	.530	1842	361.826	26.742	1.75	180	1230.78	90.967
.150	.07	.00780	.00057	.535	1818	370.976	27.418	1.80	159	1239.25	91.593
.160	.23	.00930	.00068	.540	1783	379.979	28.084	1.85	142	1246.78	92.149
.170	.63	.01360	.00100	.545	1754	388.821	28.737	1.90	126	1253.48	92.644
.180	1.25	.02300	.00169	.550	1725	397.519	29.380	1.95	114	1259.48	93.088
.190	2.71	.04280	.00316	.555	1720	406.131	30.017	2.00	103	1264.90	93.489
.200	10.7	.10985	.00811	.560	1695	414.664	30.648	2.10	90	1274.55	94.202
.210	22.9	.27785	.02053	.565	1705	423.169	31.276	2.20	79	1283.00	94.826
.220	57.5	.67985	.05024	.570	1712	431.711	31.907	2.30	69	1290.40	95.373
.225	64.9	.98585	.0728	.575	1719	440.289	32.541	2.4	62.0	1296.95	95.8580
.230	66.7	1.31485	.0971	.580	1715	448.874	33.176	2.5	55.0	1302.80	96.2903
.235	59.3	1.62985	.1204	.585	1712	457.441	33.809	2.6	48.0	1307.95	96.6710
.240	63.0	1.93560	.1430	.590	1700	465.971	34.439	2.7	43.0	1312.50	97.0073
.245	72.3	2.27385	.1680	.595	1682	474.426	35.064	2.8	39.0	1316.60	97.3103
.250	70.4	2.63060	.1944	.600	1666	482.796	35.683	2.9	35.0	1320.30	97.5838
.255	104	3.06660	.2266	.605	1647	491.079	36.295	3.0	31.0	1323.60	97.8277
.260	130	3.65160	.2698	.610	1635	499.284	36.902	3.1	26.0	1326.45	98.0383
.265	185	4.43910	.3280	.620	1602	515.469	38.098	3.2	22.6	1328.88	98.2179
.270	232	5.48160	.4051	.630	1570	531.329	39.270	3.3	19.2	1330.97	98.3724
.275	204	6.5716	.4857	.64	1544	546.899	40.421	3.4	16.6	1332.76	98.5047
.280	222	7.6366	.5644	.65	1511	562.174	41.550	3.5	14.6	1334.32	98.6200
.285	315	8.9791	.6636	.66	1486	577.159	42.657	3.6	13.5	1335.73	98.7238
.290	482	10.9716	.8109	.67	1456	591.869	43.744	3.7	12.3	1337.02	98.8192
.295	584	13.6366	1.0078	.68	1427	606.284	44.810	3.8	11.1	1338.19	98.9056
.300	514	16.3816	1.2107	.69	1402	620.429	45.855	3.9	10.3	1339.26	98.9847
.305	603	19.1741	1.4171	.70	1369	634.284	46.879	4.0	9.5	1340.25	99.0579
.310	689	22.4041	1.6558	.71	1344	647.849	47.882	4.1	8.7	1341.16	99.1252
.315	764	26.0366	1.9243	.72	1314	661.139	48.864	4.2	7.8	1341.98	99.1861
.320	830	30.0216	2.2188	.73	1290	674.159	49.826	4.3	7.1	1342.73	99.2412
.325	975	34.5341	2.552	.74	1260	686.909	50.769	4.4	6.50	1343.4141	99.291507
.330	1059	39.6191	2.928	.75	1235	699.384	51.691	4.5	5.90	1344.0341	99.337331
.335	1081	44.9691	3.323	.76	1211	711.614	52.595	4.6	5.30	1344.5941	99.378721
.340	1074	50.3566	3.721	.77	1185	723.594	53.480	4.7	4.80	1345.0991	99.416045
.345	1069	55.7141	4.117	.78	1159	735.314	54.346	4.8	4.50	1345.5641	99.450413
.350	1093	61.1191	4.517	.79	1134	746.779	55.194	4.9	4.10	1345.9941	99.482195
.355	1083	66.5591	4.919	.80	1109	757.994	56.023	5.0	3.83	1346.3906	99.511500
.360	1068	71.9366	5.316	.81	1085	768.966	56.834	6.0	1.75	1349.1806	99.717708
.365	1132	77.4366	5.723	.82	1060	779.694	57.627	7.0	.99	1350.5506	99.818965
.370	1181	83.2191	6.150	.83	1036	790.174	58.401	8.0	.60	1351.3456	99.877723
.375	1157	89.0641	6.582	.84	1013	800.419	59.158	9.0	.380	1351.8356	99.913939
.380	1120	94.7566	7.003	.85	990	810.434	59.899	10.0	.250	1352.1506	99.937221
.385	1098	100.3016	7.413	.86	968	820.224	60.622	11.0	.170	1352.3606	99.952742
.390	1098	105.7916	7.819	.87	947	829.799	61.330	12.0	.120	1352.5056	99.963459
.395	1189	111.5091	8.241	.88	926	839.164	62.022	13.0	.087	1352.6091	99.971108
.400	1429	118.0541	8.725	.89	908	848.334	62.700	14.0	.055	1352.6801	99.976356
.405	1644	125.7366	9.293	.90	891	857.329	63.365	15.0	.049	1352.7321	99.980199
.410	1751	134.2241	9.920	.91	880	866.184	64.019	16.0	.038	1352.7756	99.983414
.415	1774	143.0366	10.571	.92	869	874.929	64.665	17.0	.031	1352.8101	99.985964
.420	1747	151.8391	11.222	.93	858	883.564	65.304	18.0	.024	1352.8376	99.987997
.425	1693	160.4391	11.858	.94	847	892.08	65.934	19.0	.02000	1352.8596	99.989623
.430	1639	168.7691	12.473	.95	837	900.50	66.556	20.0	.01600	1352.8776	99.990953
.435	1663	177.0241	13.083	.96	820	908.79	67.168	25.0	.00610	1352.9328	99.995037
.440	1810	185.7066	13.725	.97	803	916.90	67.768	30.0	.00300	1352.9556	99.996718
.445	1922	195.0366	14.415	.98	785	924.84	68.355	35.0	.00160	1352.9671	99.997568
.450	2006	204.8566	15.140	.99	767	932.60	68.928	40.0	.00094	1352.9734	99.998037
.455	2057	215.0141	15.891	1.00	748	940.18	69.488	50.0	.00038	1352.9800	99.998525
.460	2066	225.3216	16.653	1.05	668	975.58	72.105	60.0	.00019	1352.9829	99.998736
.465	2048	235.6066	17.413	1.10	593	1007.10	74.435	80.0	.00007	1352.9855	99.998928
.470	2033	245.8091	18.167	1.15	535	1035.30	76.519	100.0	.00003	1352.9865	99.999002
.475	2044	256.001	18.921	1.20	485	1060.80	78.404	1000.0	.00000	1353.0000	100.000000
.480	2074	266.296	19.681	1.25	438	1083.88	80.109				
.485	1976	276.421	20.430	1.30	397	1104.75	81.652				
.490	1950	286.236	21.155	1.35	358	1123.63	83.047				
.495	1960	296.011	21.878	1.40	337	1141.00	84.331				
.500	1942	305.766	22.599	1.45	312	1157.23	85.530				
.505	1920	315.421	23.312	1.50	288	1172.23	86.639				
.510	1882	324.926	24.015	1.55	267	1186.10	87.665				
.515	1833	334.214	24.701	1.60	245	1198.90	88.611				
.520	1833	343.379	25.379	1.65	223	1210.60	89.475				

FIGURE 7

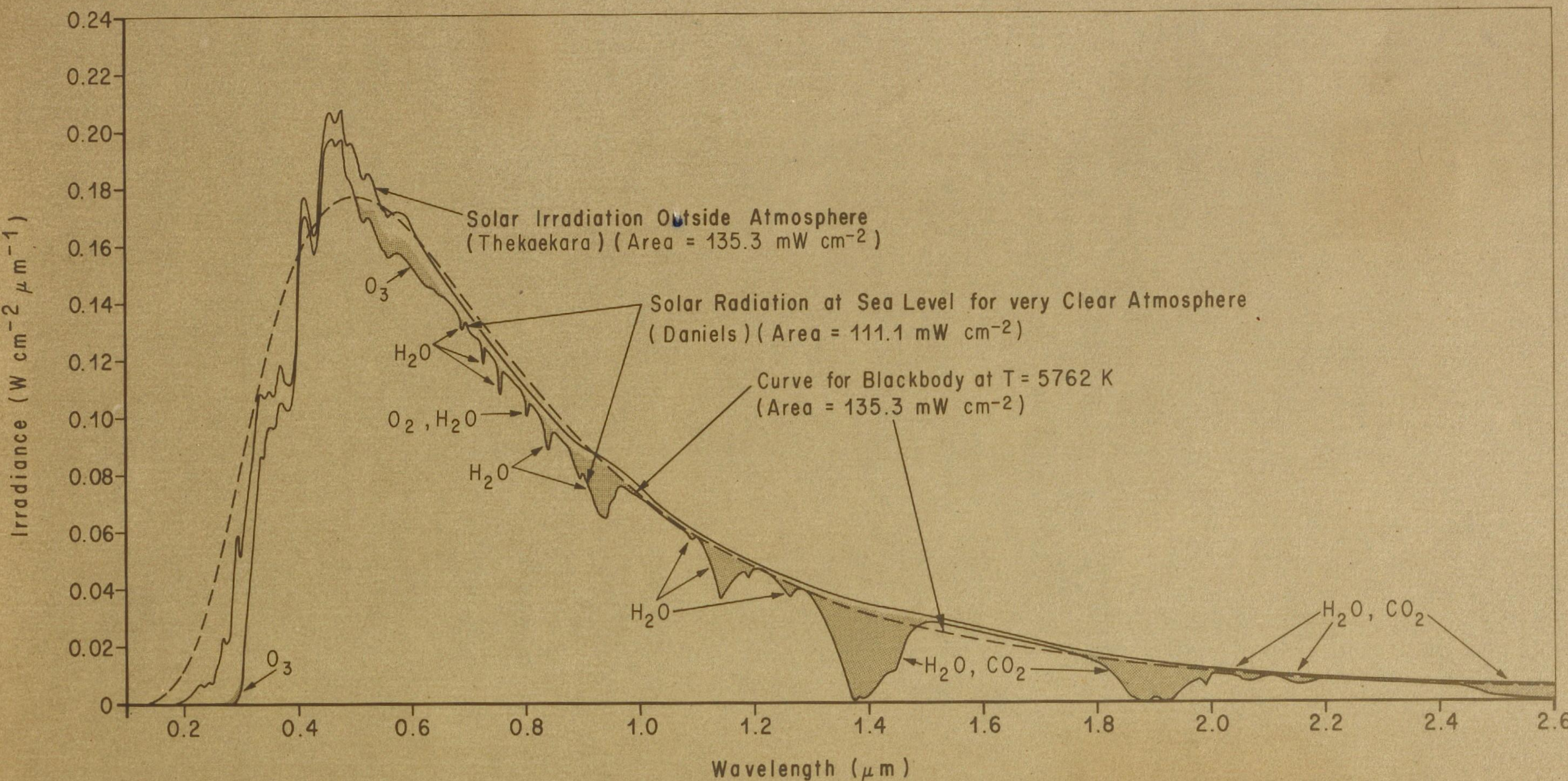

Solar Irradiation Outside Atmosphere
(Thekaekara) (Area = 135.3 mW cm-2)
Solar Radiation at Sea Level for very Clear Atmosphere
(Daniels) (Area = 111.1 mW cm-2)
Curve for Blackbody at T = 5762 K
(Area = 135.3 mW cm-2)
O3
H2O
O2, H2O
H2O
H2O
H2O, CO2
H2O, CO2
O3
Irradiance (W cm-2 μm-1)
Wavelength (μm)
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6

Table VI

IRRADIANCE (E_λ) OF THE SUN IN $W \cdot m^{-2} \cdot \mu m^{-1}$ AND INTEGRATED IRRADIANCE ($E_{0-\lambda}$) OF THE SUN IN RANGE 0 TO λ IN $W \cdot m^{-2}$
(Area normal to Sun's rays – sec Z = 1·5; TABLE MOUNTAIN, FEB 27, '72)

λ	E_λ	$E_{0-\lambda}$
·3	5	0
·31	46	·25
·32	152	1·24
·33	300	3·49
·34	375	6·96
·35	438	10·9
·36	461	15·4
·37	566	20·6
·38	557	26·2
·39	594	31·9
·40	803	38·9
·41	1038	48·1
·42	1097	58·8
·43	1068	69·6
·44	1241	81·2
·45	1386	94·3
·46	1473	108·6
·47	1520	123·6
·48	1566	139·0
·49	1545	154·5
·50	1530	170
·51	1490	185
·52	1465	200
·53	1450	214
·54	1439	229
·55	1403	243
·56	1376	257
·57	1385	271
·58	1401	285
·59	1385	299
	1	
·60	1373	312
·64	1336	367
·67	1290	406
·68	1279	419
·70	1242	444
·71	1225	456
·725	1140	474
·73	1180	480
·75	1120	503
·757	1120	511
·77	1095	525
·80	1037	557
·802	985	559
·805	1020	562
·82	995	577
·836	960	593
·84	880	597
·85	936	606
·86	910	615
·87	885	624

λ	E_λ	$E_{0-\lambda}$
·88	850	633
·89	800	641
·895	780	645
·91	770	656
·92	735	664
·93	695	671
·94	620	678
·955	725	688
·97	760	699
1·0	713	721
1·05	637	755
1·1	540	784
1·12	450	794
1·139	330	801
1·15	370	805
1·165	499	812
1·181	483	820
1·19	474	824
1·225	447	840
1·27	405	859
1·29	377	867
1·305	341	872
1·33	383	881
1·35	230	888
1·375	110	892
1·38	100	892
1·44	183	901
1·487	238	911
1·52	275	919
1·54	265	925
1·58	248	935
1·71	193	964
1·8	147	979
1·88	30	986
1·92	18	987
2·1	87	996
2·2	76	1004
2·3	65	1012
2·4	62	1018
2·5	31	1023
2·6	10	1025
3·0	0	1027

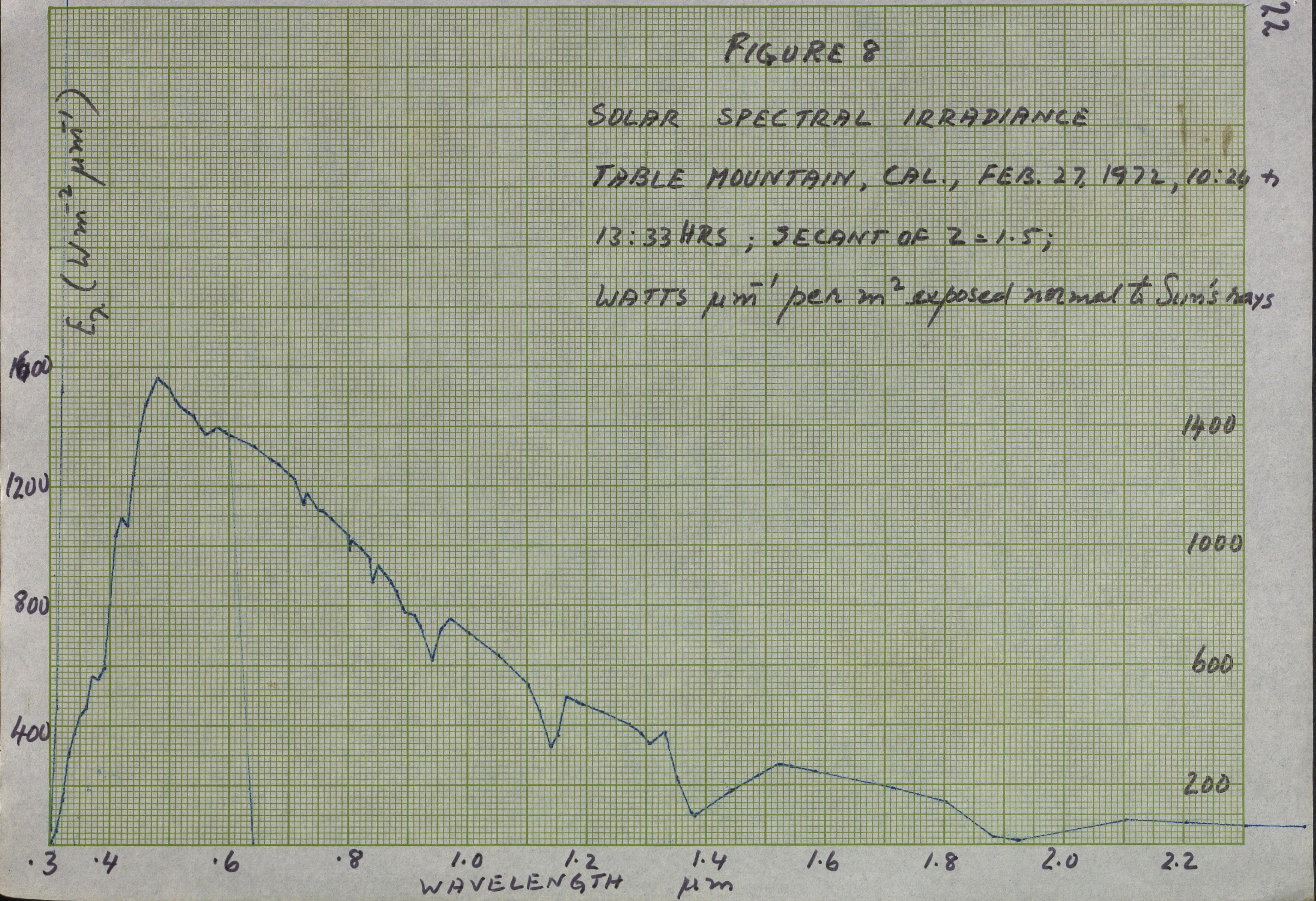


FIGURE 8
SOLAR SPECTRAL IRRADIANCE
TABLE MOUNTAIN, CAL., FEB. 27, 1972, 10:24 to
13:33 HRS ; SECANT OF Z = 1.5;
WATTS μm⁻¹ per m² exposed normal to Sun's rays
E_λ ($W m^{-2} \mu m^{-1}$)
1600
1200
800
400
1400
1000
600
200
·3
·4
·6
·8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
WAVELENGTH μm

TABLE VII

IRRADIANCE (E_λ) OF THE SUN & OF THE SKY

INTEGRATED SOLAR AND SKY IRRADIANCE IN RANGE 0 to λ ($E_{0-\lambda}$)

E_λ in $W \cdot m^{-2} \cdot \mu m^{-1}$ (Area normal to sun's rays, sec z = 1·5, for E_λ sun; horizontal area for E_λ sky)

λ	E_λ SUN	$E_{0-\lambda}$ SUN	E_λ SKY	$E_{0-\lambda}$ SKY	λ	E_λ SUN	$E_{0-\lambda}$ SUN	E_λ SKY	$E_{0-\lambda}$ SKY
·3	3	0	0	0	·88	721	558	19	115·3
·31	39	·21	48	·2	·89	679	565	15	115·4
·32	175	1·3	123	1·1	·895	669	568	14	115·5
·33	302	3·7	318	3·3	·908	649	577	11	115·7
·34	377	7·1	408	6·9	·92	576	584	4	115·8
·35	425	11	415	11·0	·93	533	590	2	115·8
·36	446	15	381	15	·94	494	595	3	115·8
·37	527	20	373	19	·958	525	604	6	115·9
·38	532	25	333	22	·976	572	614	4	116·0
·39	556	31	314	26	1·01	603	634	0	116·1
·40	769	37	384	29	1·025	594	642	0	116·1
·41	986	46	447	33	1·04	588	652		
·42	1022	57	421	38	1·05	577	658		
·43	989	67	379	42	1·08	508	674		
·44	1121	77	402	45	1·095	401	681		
·45	1273	89	437	50	1·115	306	688		
·46	1340	102	440	54	1·14	273	695		
·47	1344	116	421	58	1·165	368	703		
·48	1394	129	417	63	1·181	415	709		
·49	1330	143	351	66	1·19	426	712		
·50	1340	156	359	70	1·225	422	728	0	116·1
·51	1313	170	324	73	1·27	375	746		
·52	1290	182	257	76	1·29	343	752		
·53	1306	196	276	79	1·305	262	757		
·54	1273	208	248	82	1·33	126	762		
·55	1239	221	224	84	1·35	59	764		
·56	1224	233	190	86	1·375	0	765		
·57	1243	246	199	88	1·38	0	765		
·58	1252	258	204	90	1·44	53	766		
·59	1247	271	180	92	1·487	104	770		
·60	1228	283	170	94	1·52	147	774	0	116·1
·64	1178	331	145	100	1·54	191	778		
·67	1140	366	125	104	1·58	212	786		
·678	1119	375	104	105	1·71	170	811		
·685	1068	383	91	106	1·8	77	821		
·70	1087	399	94	107	1·88	0	825		
·71	1038	409	85	108	1·92	0	825		
·715	1005	414	81	108	2·1	20	827		
·725	982	424	65	109·0	2·2	70	831		
·735	997	434	70	109·6	2·3	62	838		
·742	1009	441	67	110·1	2·4	47	843		
·748	958	447	63	110·5	2·5	24	846		
·755	897	454	49	110·9	2·6	0	848		
·773	913	470	53	111·8	3·0	0	848	0	116·1
·792	923	487	64	112·7					
·815	843	507	36	113·7					
·828	775	518	31	114·1					
·839	754	526	20	114·4					
·858	758	541	23	114·8					
·868	781	549	21	115·0					

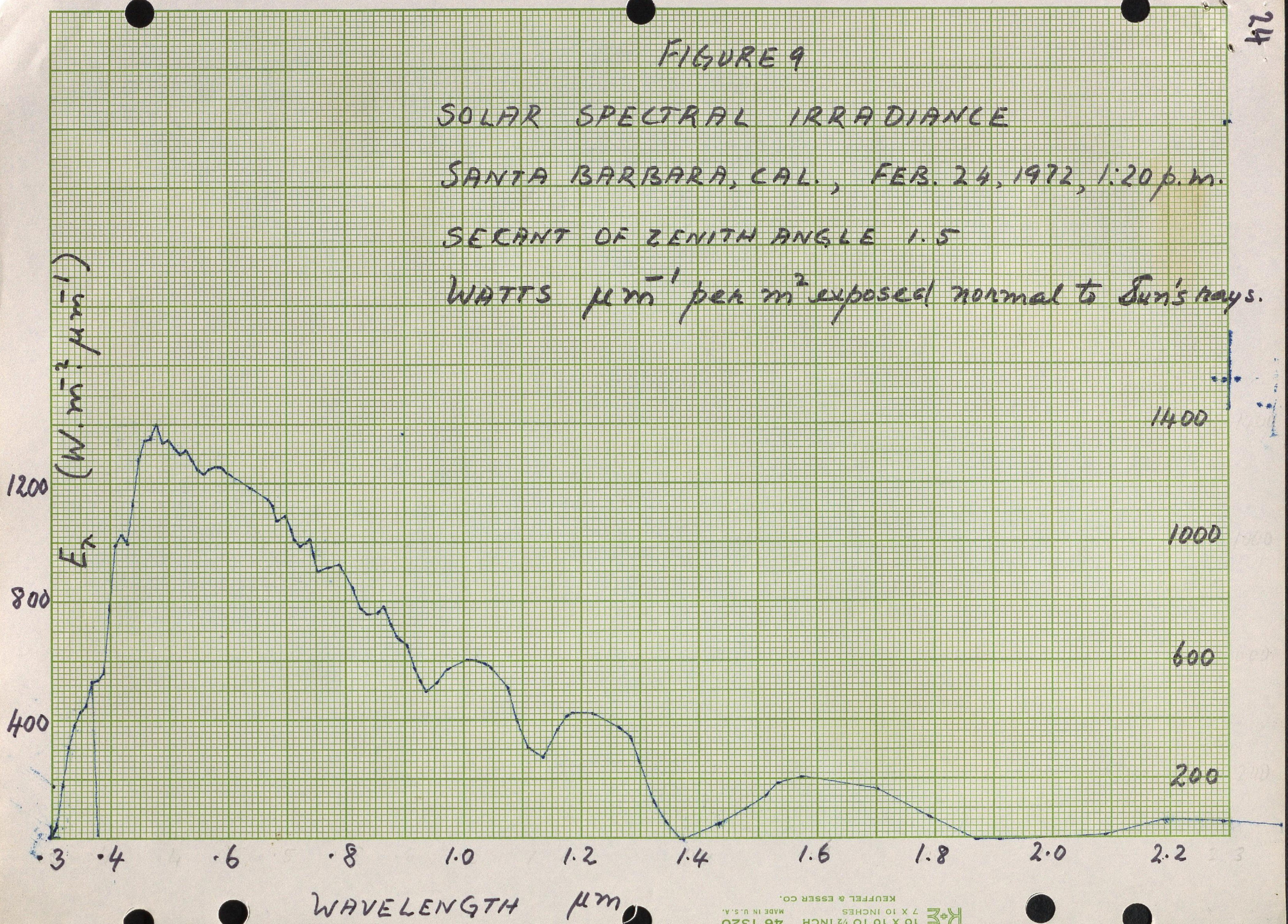


FIGURE 9
SOLAR SPECTRAL IRRADIANCE
SANTA BARBARA, CAL., FEB. 24, 1972, 1:20 p.m.
SECANT OF ZENITH ANGLE 1.5
WATTS μm⁻¹ per m² exposed normal to Sun's rays.
E_λ (W.m⁻².μm⁻¹)
1200
800
400
1400
1000
600
200
·3
·4
·6
·8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
WAVELENGTH μm

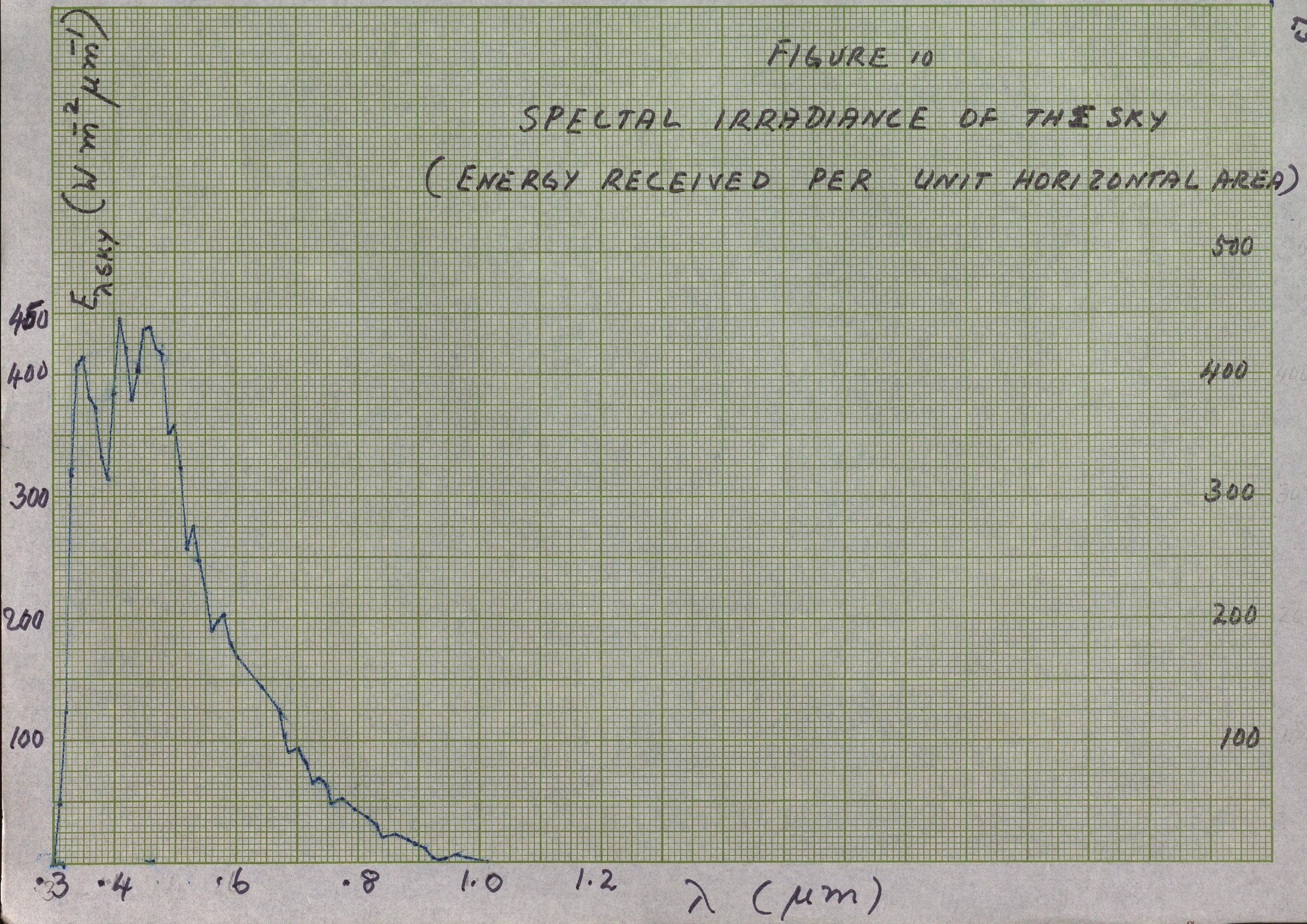


FIGURE 10

SPECTAL IRRADIANCE OF THE SKY

(ENERGY RECEIVED PER UNIT HORIZONTAL AREA)